A TURBULENT WALL JET ON A ROUGH SURFACE

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ABSTRACT

This paper reports measurements of the mean velocity and turbulence quantities in smooth and rough wall turbulent wall jets created in an open channel flow. The measurements were obtained using a laser-Doppler anemometer. The Reynolds numbers based on the jet exit conditions are in the range $7000 < Re_j$ ($= U_jb/\nu$) < 14500. The turbulence intensity in the central region of the jet exit varied from 3 to 5 percent. The results show that the inner layer of the mean velocity field and the skin friction characteristics are significantly altered by surface roughness but the turbulence quantities are nearly independent of roughness effects.

INTRODUCTION

A turbulent wall jet is a shear flow directed along a wall, where by virtue of the initially supplied momentum, at any downstream station, the streamwise velocity over some region within the flow exceeds that in the external stream (Launder and Rodi, 1981). A sketch that serves to define some of the nomenclature is shown in Figure 1. In this figure, x and y denote distances in the streamwise and wall-normal directions, respectively; U and V are the streamwise and wall-normal components of the mean velocity; U_j is the exit velocity; b is the slot height; U_m is the local maximum velocity; y_m and $y_{1/2}$, respectively, denote the wall-normal locations where U_m and $0.5U_m$ occur. In this paper, y_m and $y_{1/2}$ will be referred to as the inner layer thickness and the jet half-width. From a research perspective, a turbulent wall jet may be thought of as a composite flow made up of two interacting shear layers: an inner layer ($y \leq y_m$) which possesses many of the characteristics of a turbulent boundary layer, and an outer region ($y > y_m$) which is structurally similar to a free plane jet. The interaction between the inner and outer layers creates a complex interface that is characterized by intense mixing. This region is still poorly understood and poses the greatest challenge to numerical models.

Turbulent wall jets have been extensively investigated in view of their diverse technological applications, e.g., in boundary layer control and film cooling technology. Studies of turbulent wall jets also promote a better understanding of the interaction between boundary layer and free shear flows. The wall jet literature existing prior to 1981 was critically reviewed by Launder and Rodi (1981, 1983) and will not be repeated here. It should, however, be pointed out that the experiments considered in these reviews were made using pitot-tube and/or conventional thermal anemometers. In spite of the large body of literature existing at the time of these reviews, accurate, consistent and comprehensive data sets were lacking. A number of studies were carried out subsequently to address some of the important research questions that were unanswered. Dakos et al. (1984) investigated a heated wall jet on both plane and curved surfaces using a hot-wire anemometer. Karlsson et al. (1992) used a high spatial resolution LDA system to obtain

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measurements of the mean velocities and turbulence quantities down to the wall, and Abrahamsson et al. (1994) reported hot-wire measurements in a large enclosure at different Reynolds numbers. Schneider and Goldstein (1994) and Venas et al. (1999) showed that wall jet measurements obtained using pitot-tube and hot-wire probes deviate significantly from the data obtained using LDA and pulsed hot-wires in the outer region of the flow. Although most practical flow systems in which wall jets are found may be hydraulically rough, measurements of turbulent wall jets on rough surfaces are rather scarce. Perhaps, with the exception of the pitot-tube measurements reported by Rajaratnam (1965) and Sakipov (1975), the effects of surface roughness on the turbulence structure of a wall jet are virtually unknown. The objective of the present study is to investigate the mean and fluctuating characteristics of a turbulent wall jet on a rough surface. Since the present flows were created in an open channel and may be influenced by the characteristic high background turbulence levels, the data are compared to previous results in the literature so that the extent to which background turbulence modifies the flow can also be assessed.

EXPERIMENTAL PROCEDURE

The wall jet was created in an open channel flume 10 m long, 0.8 m wide and 0.6 m deep. The sidewalls of the flume were made of transparent tempered glass to facilitate velocity measurements using a laser Doppler anemometer. The inlet of the nozzle was placed 3 m downstream of the channel contraction. The thickness (t) and height (b) of the slot was 6 mm and 10 mm, respectively. The ratio of the width (w) of the slot to the slot height was $w/b = 79$. Further details of the open channel flume and wall jet facility are available in Tachie (2001) and are avoided here for brevity.

The velocity measurements were obtained on hydraulically smooth and rough surfaces. The surface roughness was created using 1.2-mm nominal mean diameter sand grains. The sand grains were carefully attached using double-sided tape to ensure a uniform distribution. The velocity measurements were obtained using a two-component fiber-optics LDA system configured in a backscatter mode. The LDA system was powered by a 300 mW Argon-Ion laser (Dantec Inc.) The optical elements include a Bragg cell, a 1.96 beam expansion unit and a 500 mm focusing lens. The configuration of the present two-component system did not allow data to be obtained in the very near-wall region. Therefore, a single-component LDA system was used to measure the streamwise component of the mean velocity and its fluctuation down to the wall. It was verified that the streamwise component of the mean velocity and its fluctuations obtained using the two-component LDA agree (within measurement uncertainties) with the corresponding data obtained with the one-component system. In this study, no artificial seeding was used since there were enough scattering particles (i.e. natural occurring hydrosols) in the flow. The validated data rate varied from 7 Hz in regions of low velocity to 80 Hz in regions of high local velocity. The maximum sampling time and sample size at a measuring location was set to 1500 seconds and 15000, respectively, for the two-component measurements. Depending on the local velocity, typical sample size varied from 5000 to 10000 for the one-component measurements, and 10000 to 15000 in the case of the two-component measurements. In contrast to many previous experiments (e.g. Karlsson et al., 1992; Abrahamsson et al., 1994; Schneider and Goldstein, 1994), where top-hat velocity profiles were reported, the present exit mean velocity profiles are flat only over 30 to 40 percent of the slot. The turbulence intensity in the central region of the jet exit varied from 3 to 5 percent, which is an order of magnitude higher than values reported in the literature.

Following the methodology outlined by Yanta and Smith (1973) and Schwarz et al. (1999), the following uncertainty estimates were obtained at 95 percent confidence level. In the inner region, the measurement uncertainty in the mean velocities (U and V) and the turbulence intensities (u_{rms} and v_{rms}) is less than 1 percent, while the maximum uncertainty in the Reynolds shear stress is 12 percent. The uncertainty in the outer region is substantially higher due to a reduction in sample size and high local turbulence levels. Typical estimates in the outer region are as follows: ±2.5 percent for U and V, and ±5-10 percent for u_{rms} and v_{rms}.

A summary of the test conditions is presented in Table 1, where SI-1, SI-2 and SI-3 denote single-component measurements on a smooth surface; RI-1, RI-2 and RI-3 are single-component measurements on a rough surface; SII and RII denote two-component measurements on smooth and rough surfaces, respectively; U_j is the maximum velocity at the jet exit, U_b is the bulk mean velocity determined from mass flow rate measurement using an electronic weighing tank, $Re_j = U_j b/\nu$ and $Re_b = U_b b/\nu$. The bulk mean velocities were also determined by integrating the exit mean velocity profiles. The differences between the bulk mean velocity obtained from the exit mean profile and the corresponding value obtained from mass flow rate measurements were less than 3 percent. Measurements were obtained at the jet exit ($x/b = 0$) and several streamwise locations up to 100 slot heights ($x/b = 100$) in order to examine the streamwise development of the flow. The results revealed that close to the jet exit ($x/b < 20$), the flow was not fully developed while measurements obtained at $x/b > 80$ were significantly influenced by reversed flow and three-dimensional effects (Tachie, 2001).

Table 1: Summary of test conditions

Test	Surface	U_j (m/s)	U_b (m/s)	Re_j	Re_b
SI-1	smooth	1.389	1.202	14000	12100
SI-2	smooth	1.054	0.868	10000	8700
SI-3	smooth	0.759	0.595	7500	6000
SII	smooth	1.341	1.146	13400	11500
RI-1	rough	1.394	1.185	14000	12000
RI-2	rough	1.204	0.997	12000	10000
RI-3	rough	0.721	0.584	7200	5900
RII	rough	1.304	1.117	13100	12000

RESULTS AND DISCUSSION

Decay and Growth Rates

The variation of the maximum local mean velocity (U_m) with streamwise distance for both smooth and rough surfaces is shown in Figure 2. The exit maximum velocity (U_j) and the slot height (b) are used as the normalizing velocity and length scales, respectively. Figure 2 suggests a higher decay rate for the rough surface compared to the smooth wall data, especially in the region of flow development.

Figure 3 compares the inner layer thickness (y_m) for the smooth and rough wall data. The lines are only for the purpose of visual aid. The values of y_m are higher for the rough wall data. The spread rates for the jet-half width (not shown) vary from 0.085 to 0.090 depending on exit Reynolds number, but are independent of wall conditions (Tachie 2001). Such a Reynolds number dependence of the spread rate has also been reported by Wygnaski et al. (1992) and Abrahamsson et al. (1994). The present spread rates are substantially higher than the values reported in earlier turbulent wall jet studies but lower than typical values for free plane jets.

Transverse Velocity Profiles

Consideration is now turned to the mean velocity and Reynolds stresses in the transverse direction. All the profiles examined in this section were obtained at x/b = 40 or 50. At these streamwise stations, the mean velocities and their higher order moments are self-similar, and any three-dimensional or secondary flow effects are also minimal. Unless otherwise specified in the following discussion, x/b = 50.

Mean Velocity Profiles. The mean velocity profiles on smooth and rough surfaces in outer coordinates (U_m, $y_{1/2}$) are plotted in Figure 4. The LDA data of Karlsson et al. (1992) [KEP] are also shown for comparison. In spite of the relatively higher background turbulence levels observed in the present open channel experiments, the present smooth wall data are in good agreement with the previous data. The smooth and rough wall profiles are nearly indistinguishable in the outer region ($y > 0.5y_{1/2}$). The near-wall data for the present smooth and rough surfaces are shown in Figure 5. This figure shows a very distinct effect of surface roughness on the mean velocity profiles. More specifically, the rough wall profiles are less 'full' compared to the smooth wall data. Furthermore, the position at which the local maximum velocity occurs is farther removed from the wall in the case of the rough data compared to the smooth wall profiles.

The mean velocity profiles for both smooth and rough surfaces in inner coordinates are plotted in Figure 6. For the smooth wall data, the friction velocities were determined by fitting a fifth order polynomial ($U^+ = y^+ + c_4 y^{+4} + c_5 y^{+5}$) to the near-wall data. The values of c_4 and c_5 obtained in the present experiments are similar to the values recommended by Eriksson et al. (1998) and George and Castillo (1997). These values are also similar to those obtained in our previous boundary layer analysis (Tachie et al., 2000; Tachie, 2001). The present smooth wall data and those obtained by Karlsson et al. (1992) [KEP] show that a well-defined overlap region exists although the extent of overlap is relatively narrower than observed in turbulent boundary layers. In the case of the rough wall data, a Clauser plot technique was used to determine the friction velocity. It is evident from Figure 6 that the skin friction characteristics are significantly altered by surface roughness. Figure 6 also supports the traditional notion of a similarity between the inner regions of a turbulent wall jet and a turbulent boundary layer.

Reynolds Stresses. Figure 7 examines the effects of surface roughness on the streamwise component of the normal Reynolds stresses (u_{rms}^2). The data of Karlsson et al. (1992) [KEP] and Abrahamsson et al. (1994) [AJL] are also shown for comparison. The present smooth wall data compare reasonably well to the data of [KEP] and [AJL] in the inner layer, but are consistently higher than those of [KEP] and [AJL] in the outer region. This may be due to the high background turbulence levels in open channel flows. Figure 7 shows no distinct roughness effects over most of the flow. A closer examination of the very near-wall region shows, however, that the turbulence levels are relatively higher on the rough surface.

The wall-normal Reynolds stress (v_{rms}^2) are shown in Figure 8. As mentioned earlier, we were unable to obtain measurements of v_{rms} (and uv) in the very near-wall region due to hardware limitations. The much higher values of v_{rms}^2 observed in the present study compared to the profiles reported by [KEP] and [AJL] are due to the characteristic high background turbulence levels in open channel flows. These influences notwithstanding, no distinct effects of surface roughness are observed in Figure 8.

The effects of roughness effects on the Reynolds shear stress are examined in Figure 9. The LDA data of [KEP] and Schneider and Goldstein (1994) [SG], and the hot-wire data of [AJL] are shown for comparison. Although the measurements obtained in different studies show considerable variation, the present smooth and rough wall data compare reasonably well. This and the observations made in Figures 7 and 8 are in contrast to recent rough wall boundary layer measurements (e.g. Krogstad and Antonia, 1999; Tachie, 2001) in which surface roughness was observed to increase the turbulence fluctuations and Reynolds shear stress over a significant part of the flow.

CONCLUSIONS

The present paper examined surface roughness effects on turbulent wall jets created in an open channel flow. The results show that the inner region of the mean velocity profile and the skin friction characteristics are significantly altered by surface roughness. On the other hand, the Reynolds stresses do not show the same sensitivity to surface roughness as has been documented in recent rough wall turbulent boundary layers. It is also observed that surface roughness increases the inner layer thickness but does not alter the spread rate. This observation supports the premise of previous numerical study (e.g. Gu and Bergstrom, 1994) that a wall jet is a complex flow in which the mechanisms of near-wall damping are not the same as in a simple boundary layer.

An immediate conclusion of the present study is that any roughness effects in a turbulent wall jet are limited to the inner region, at least for flows with external turbulence levels close to those in the present study. One would also expect heat and mass transfer rates at the surface to be significantly altered by surface roughness.

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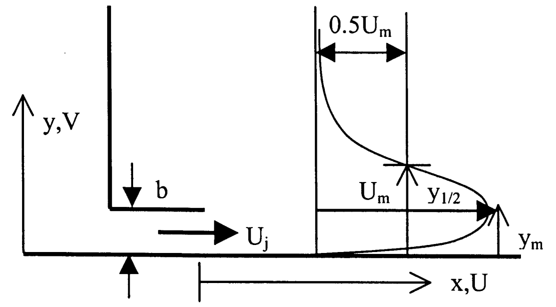

Figure 1: A definition sketch of a turbulent wall jet

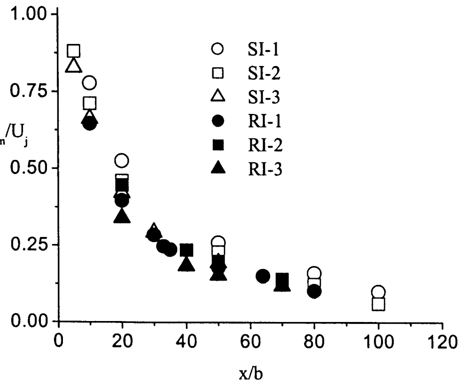

Figure 2: Velocity decay on smooth and rough surfaces

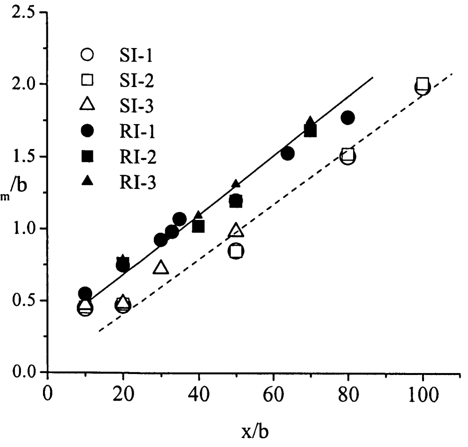

Figure 3: Growth of the inner layer thickness

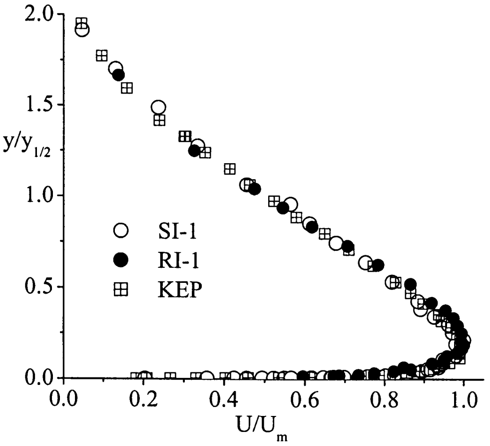

Figure 4: Mean velocity profiles on smooth and rough surfaces in outer coordinates

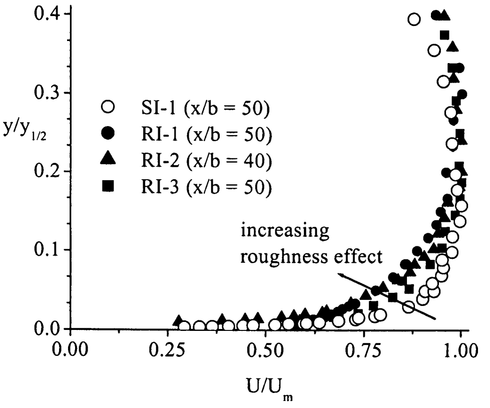

Figure 5: Near-wall mean velocity profiles in outer coordinates

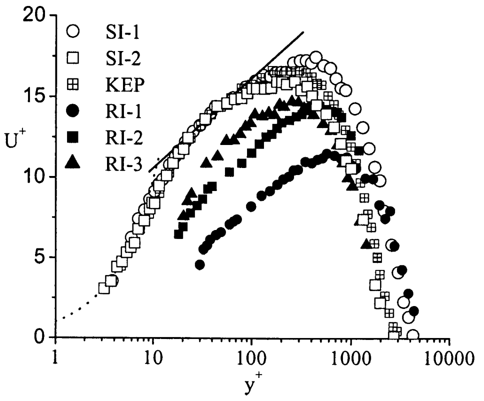

Figure 6: Mean velocity profiles on smooth and rough surfaces in inner coordinates (dashed line: $U^+ = y^+$; solid line: $U^+ = 2.44\ln y^+ + 5.0$)

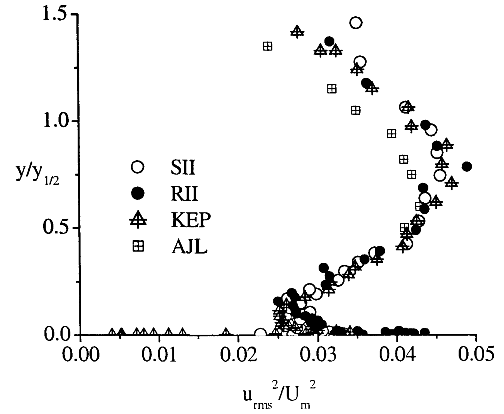

Figure 7: Streamwise turbulence intensity on smooth and rough surfaces

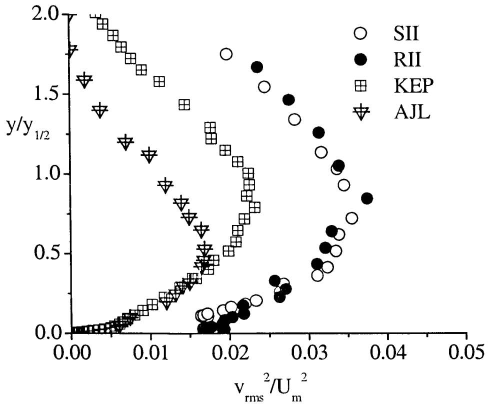

Figure 8: Wall-normal turbulence intensity on smooth and rough surfaces

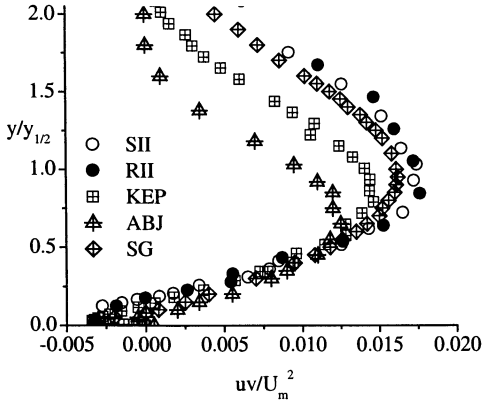

Figure 9: Reynolds shear stress on smooth and rough surfaces